Analysis of Turbulent Premixed Flames at the Laboratory Scale

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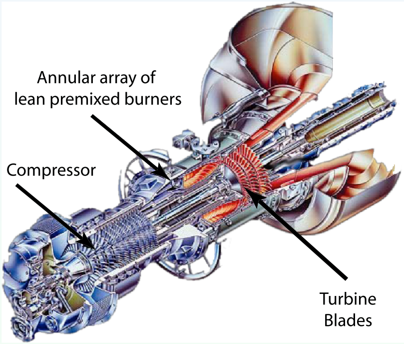
Motivation

DOE's office of Fossil Energy (FE) has a particular interest in ultra-low (< 2 ppm NO_x) emissions, fuel-flexible turbines for power generation. Current strategies suggest:

- Lean premixed systems (low exhaust temperature results in low NO_x)
- Array of alternative fuels
  - Hydrogen
  - Syngas mixtures ($CO + H_2$)
  - Other...Hydrogen + hydrocarbons resulting from gasification processes (coal, biomass, etc.)



Low-swirl burner

Low-swirl burner technology developed at LBL is a leading candidate for meeting requirements of low-emissions turbines


2" Laboratory Burner

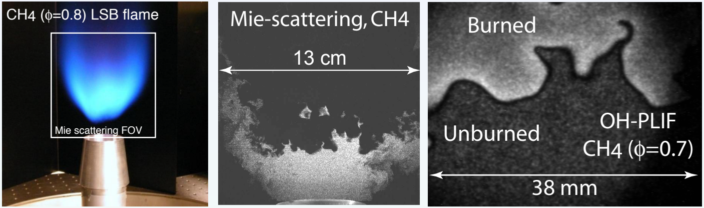

1" Burner (5kW, 17 KBtu/hr)


28" Burner (44MW, 150 MBtu/hr)

- Scalable configuration for atmospheric and high-pressure
- Stabilized by swirl-induced flow divergence (no pilot)
- Simple geometry ammenable to simulation

Standard flame theory, lean CH_4 flames

Characterizing experimental low-swirl flames

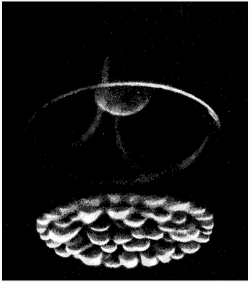


CH_4-air flames well-approximated by “standard flame model”

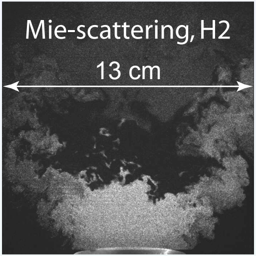
- Continuous flame separates fuel from products
- Propagates as flat flame, enhanced by surface wrinkling
- Simple model is basis of engineering design/analysis
- Model also used to interpret experimental diagnostics (e.g. Mie-scattering → flame position)

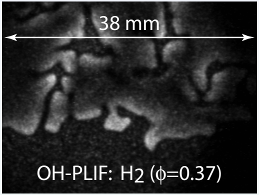
Cellular burning in lean H_2 flames

Freely propagating H_2 flames burn in "cellular" patterns



(Thermo-diffusively unstable flame, photo 1959)





- Highly variable burning, regions of local flame extinction
- Temperature, fuel profiles not sensible "progress variables"
- Standard turbulent flame model is not applicable

Quantitative analysis requires detailed simulation

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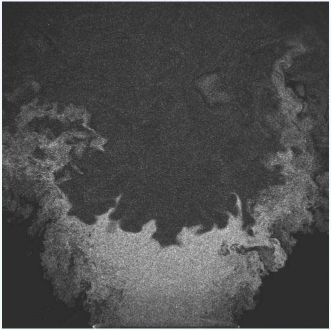
Relevant scales: turbulent laboratory LSB flame

Spatial Scales

- Domain $L \approx 10$ cm
- Flame thickness $\delta_T \approx 1$ mm
- Integral scale $\ell_t \approx 2 - 6$ mm

Velocity Scales

- Flame speed $\mathcal{O}(10^2)$ cm/s
- Mean Flow $\mathcal{O}(10^3)$ cm/s
- Acoustic Speed $\mathcal{O}(10^5)$ cm/s



An ideal solution approach exploits inherent separation of scales

Solution Approach

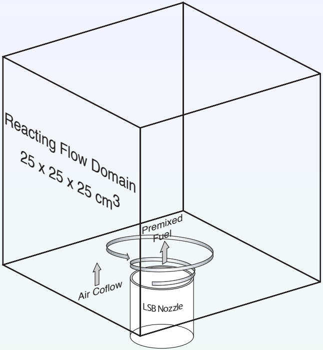
Key observations:

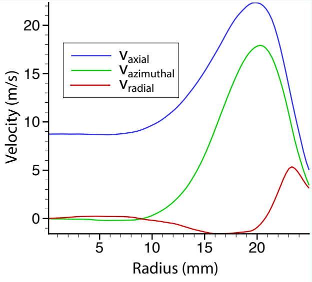
- Open laboratory turbulent flames are low Mach number
- Regions requiring high-resolution are localized in space

Our approach: Exploit known scale separations

- Low Mach number formulation
  - Eliminate acoustic waves (and the need to resolve them)
  - Flow expansion at flame leads to global evolution constraint
- Adaptive mesh refinement
  - Dynamically place fine mesh only where needed
  - Synchronized time-stepping across refinement levels
- Parallel architectures
  - Distributed memory, communication via MPI
  - Dynamic load balancing of heterogeneous work associated with detailed chemistry at flame

Low Swirl Burner Simulations





Strategy: Rectangular domain. Nozzle outflow becomes inflow boundary condition

- Mean flow and turbulent intensities from measured data
- Impose synthetic turbulence as a perturbation to mean inflow (u', ℓ_t, from experimental data)

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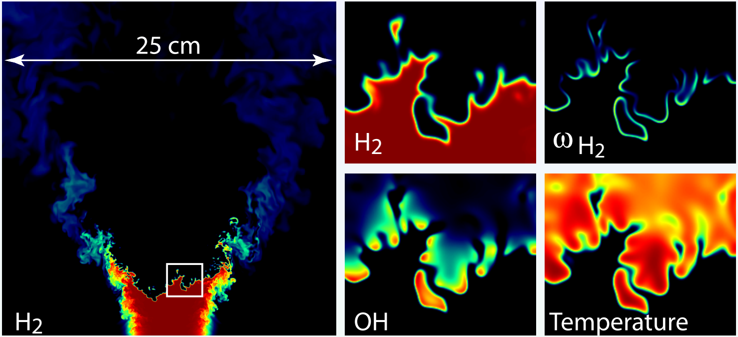
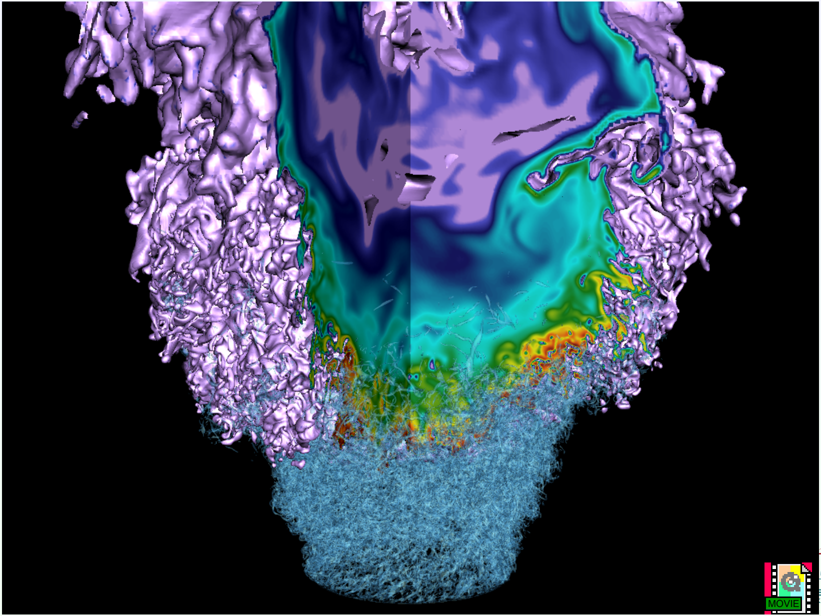
Typical profile of simulated LSB H_2 flame



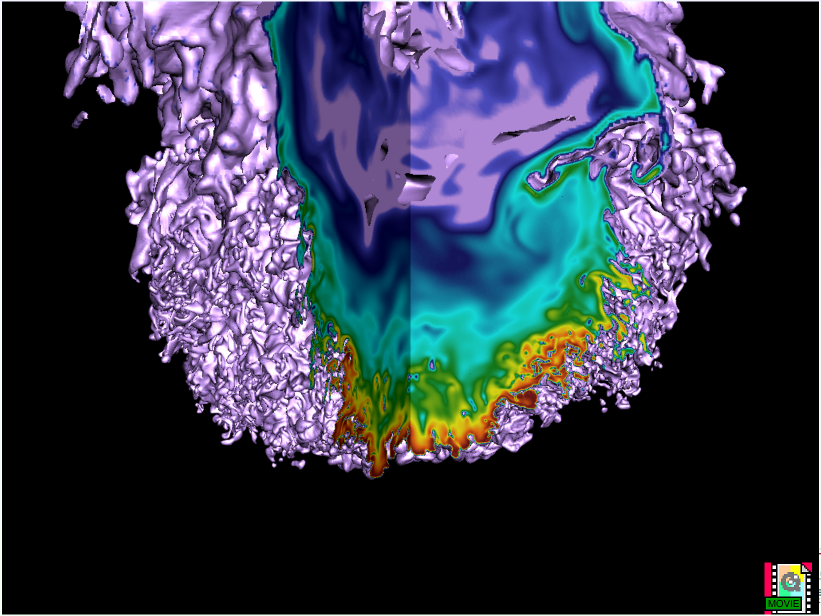
- Detailed kinetics and differential transport models (9 species, 27 reactions)
- Quasi-steady solution, slice taken from vertical midplane
- Effective resolution 2048^3, 4% of domain refined
- Flame thickness $\delta_T \sim 800\mu$m ($\Delta x \sim 122\mu$m)*

** Possible through INCITE allocation*

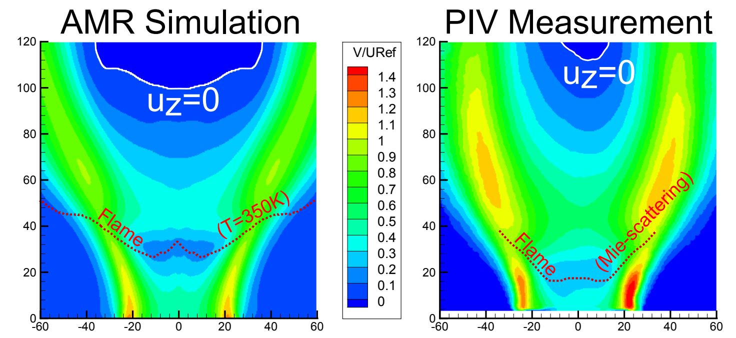
LSB solution - log(OH) + vorticity magnitude



LSB solution - log(OH)



Comparisons with mean velocity from LSB experiment



- Simulation reproduces many salient LSB flame features, including recirculation zone (vertical velocity shown here)
- Discrepancies (flame position, velocity) likely due to (1) boundary data, and (2) lack of sufficient statistics
  - Inlet data scaled from experimental measurements at lower flow rate, difference suggests *Re*-dependence of flow field
  - Recent data suggests 30% azimuthal fluctuations in experimental means
  - Azimuthally averaged simulation data - poor statistics at core

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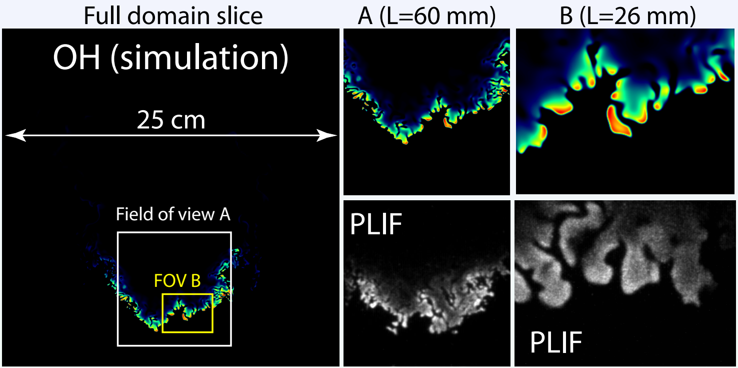
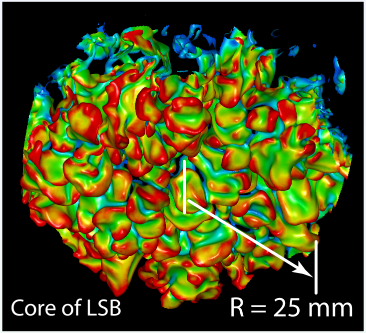
Comparisons with OH-PLIF from LSB experiment

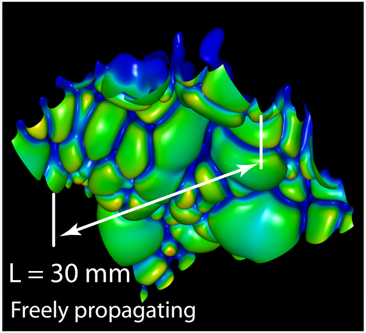


- Comparison of OH slice with typical OH-PLIF measurements, global and fine scales
- Instantaneous large- and fine-scale flame shape/extremely similar, in terms of shape and variability

Comparisons with freely propagating flame

Isotherms colored by local fuel consumption rate (same scale)





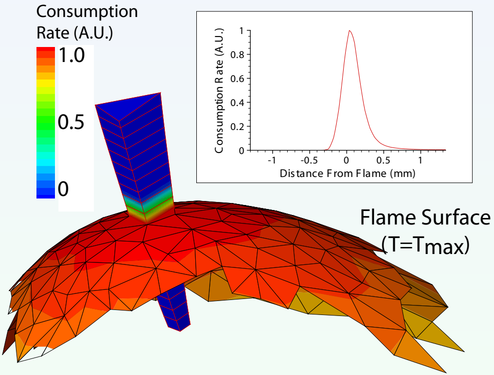
- On right, flame propagates into quiescent fuel
- “Natural” cellular structure predominantly spherical
- Turbulence changes character of wrinkling (becomes more cylindrical), enhances local variability
- The “standard model” (thin flame) clearly fails here

Detailed flame analysis

Construct flame-centric coordinate system based on T.
Element bounds follow integral curves of ∇T

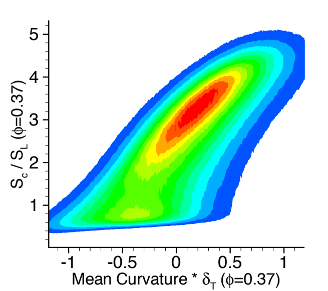
Local consumption speed

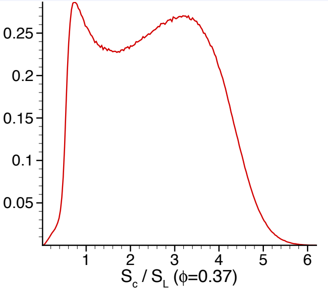
$$s_c = \frac{1}{A\,(\rho Y_{\mathrm{H}_2})_{\mathrm{in}}} \int_\Omega \omega_{\mathrm{H}_2}\, d\Omega$$



“Flame” statistics conditioned on threshold for s_c

Curvature vs. local burning speed



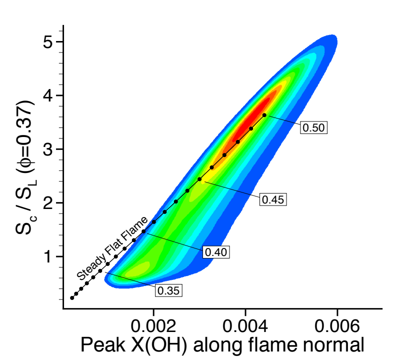


- Local burning enhanced 3-4 $\times$ flat flame value, even in flat regions
- Considerable flame surface burning at very low levels

Burning mode far outside simple turbulent flame models

Detailed flame analysis

Example: Use simulation data to find non-local correlations — i.e. does high values of OH correspond to large "nearby" s_c?



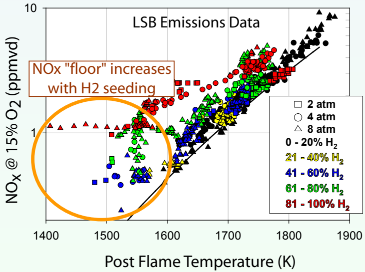
Search flame normals for peak OH. correlated to s_c?

Yes! Suggests that OH-PLIF may be used to quantitatively measure "local" (nearby) consumption

Summary

Methodology to simulate realistic turbulent lab-scale flames

- Detailed chemistry and transport (no “turbulence” models)
- Efficient AMR algorithm exploits scale separations
- Flame detail supplements experimental data, validates interpretation of diagnostics



Future work

- Detailed kinetics to include emissions chemistry – investigate experimentally obsesrved NO_x “floor” (see figure)
- High-pressure simulations relevant to turbine application
- Syngas and other lean mixed fuels from gasification processes